Articles

Centennial of Röntgen's Discovery of X-rays

RICHARD I. FRANKEL, MD, MPH, *Honolulu, Hawaii*

November 8, 1995, marked the 100th anniversary of Wilhelm Conrad Röntgen's discovery of x-rays. This remarkable scientific achievement has had an effect on medicine and science that has been matched by few other advances. I will briefly review the events leading up to Röntgen's discovery and the subsequent development of radiology as a discipline.

(Frankel RI: Centennial of Röntgen's discovery of x-rays. West J Med 1996; 164:497-501)

November 1995 marked the centennial of one of the great discoveries of science. On November 8, 1895, Wilhelm Conrad Röntgen (1845 to 1923) discovered a mysterious new ray that he later called the "x-ray," signifying the unknown and puzzling nature of this type of radiation or perhaps his own modesty.[1] This name has, of course, remained in use for the intervening century, although some still refer to x-rays as "roentgen rays," a term that was used by others shortly after Röntgen's discovery in recognition of his great achievement. In view of the pivotal role of this discovery in the development of many aspects of medical science, including diagnosis, treatment, epidemiology, public health, and pathophysiology, it is appropriate to commemorate Röntgen's seminal work with a brief review.

Röntgen was born in Lennep in what is now the Rhineland region of Germany in 1845. His parents were first cousins.[2] His mother's ancestors were from Holland, and the Röntgen family moved to Apeldoorn, Holland (now the Netherlands), when Wilhelm was 3 years of age. His father was a merchant. Because of the move, the family lost their Prussian citizenship and became Dutch citizens in 1848, the year of their move.[3]

An average student in primary and secondary school, Röntgen entered the Utrecht Technical School in Holland in 1862. Completion of that curriculum would have prepared him only to enter a technical high school; he would not have qualified for entry into a university. He did not complete the curriculum, however, being expelled because he refused to name a fellow student who had mocked the teacher in class.[3] After auditing mostly science courses at the University of Utrecht, Röntgen moved to Zürich, Switzerland, in November 1865 to enroll as a student of mechanical engineering at the federal Polytechnical School, graduating as a mechanical engineer in 1868.[4] His only physics course there was one semester in technical physics taught by R. J. E. Claussius (1822 to 1888), a German mathematical physicist who is regarded as the father of thermodynamics and who is honored by having one of the moon's craters named after him. There is no evidence, however, that Claussius had any specific influence on the direction of Röntgen's career.

After graduation, Röntgen remained in Zürich as a graduate student in mathematics at the University of Zürich. His mentor was August Kundt, an authority in the theory of light. Röntgen's first experiments at Zürich concerned the properties of gases and proved to be important in his subsequent discoveries. His doctoral thesis, *Studien über Gase* ("Studies on Gases"), led to his being awarded the PhD degree in 1869 and also led to his appointment as assistant to Kundt. Röntgen returned to his native Germany in 1870 when he followed Kundt to the University of Würzburg in Bavaria. He again followed his mentor in 1872 when Kundt was appointed to the chair of the department of physics at the Kaiser Wilhelms University in Strassburg. Röntgen's initial faculty appointment came at that same institution in 1874.

Over the next five years, Röntgen had appointments as professor in physics and mathematics in Hohenheim and associate professor in theoretical physics at Strassburg. His experimental work during this time included various studies of gases and also measurements of the discharges of electricity through conductors.

Cathode rays had been discovered by Geissler and others in the 1850s.[5] These rays consist of electrical current that is emitted from the cathode end of a vacuum tube when a high-tension electrical discharge is passed through it, and their discovery came because of the fluorescence produced when the rays struck fluorescing materials. Such a tube had been developed in 1869 by Hittorf and later modified in 1879 by Crookes by altering the shape.[6] These tubes had relatively thick glass walls. As the vacuum increased, the passage of current decreased until it would not pass through the tube. The most important experiments with cathode rays were conducted by Philipp Lenard, Director of the Physical Institute at Heidelberg University. In 1892 Lenard constructed a glass vacuum tube containing a window and covered this window with a thin layer of aluminum. He demonstrated that the cathode rays passed through the aluminum to the out-

From the Department of Medicine, University of Hawaii at Manoa John A. Burns School of Medicine, Honolulu.

Reprint requests to Richard I. Frankel, MD, MPH, Dept of Medicine, University of Hawaii John A. Burns School of Medicine, 1356 Lusitana St, 7th Floor, Honolulu, HI 96813-2427.

side, made the air outside the tube electrically conductive, were absorbed in the first few centimeters of air, caused luminescence of certain fluorescent salts, and darkened a photographic plate.[3] Röntgen repeated some experiments regarding the effects of cathode rays on air and hydrogen and was so stimulated by this work that he dropped his other research and worked exclusively on cathode rays.

In his critical series of experiments, Röntgen completely covered a Lenard tube with cardboard and foil to prevent any visible light from escaping from the tube. He directed the cathode rays toward a small screen coated with barium platinocyanide, a fluorescent material. He confirmed that the cathode rays caused fluorescence if the coated screen was placed close to the window of the tube. Knowing that Hittorf and Crookes tubes produced light when current was passed through them, he postulated that they might also produce cathode rays that caused fluorescence, but that this fluorescence might be obscured by the luminescence. He therefore completely covered a Crookes tube with cardboard and showed that no light passed through the cover when current was passed through the tube. Just before he moved to the next phase, when he planned to set up a barium platinocyanide-coated screen to look for cathode ray fluorescence, he happened to note a faint green light shimmering on a nearby bench. (The actual color perceived by Röntgen is of some interest because he was color blind![2]) He confirmed this observation on repeating the experiment and noted that the intensity of the green color fluctuated along with the fluctuating electric current. He discovered that the light was coming from the barium platinocyanide-coated screen that was lying on the bench and was to have been used for the next experiment. He showed that the fluorescence was produced even when the screen was at some distance from the tube, thus proving that something other than cathode rays was responsible for the fluorescence.

That Friday, November 8, 1895, and over the ensuing weekend, Röntgen repeated and expanded his work and documented his activities. He demonstrated that these rays could penetrate not only glass and air but a variety of materials, including various metals. He demonstrated that a thin sheet of lead completely blocked them. He also inferred that they were in fact rays because they traveled in straight lines and created shadows of the type that would be created by rays. While studying the ability of lead to stop the rays, Röntgen held a small piece of lead between his thumb and index finger and placed it in the path of the rays. He noted that he could distinguish the outline of the two digits on the screen and that the bones appeared as darker shadows than did the surrounding soft tissue. This was the first x-ray image of a part of the human body. Thus, an amazing amount of the foundation of clinical radiology was established that first weekend!

Röntgen continued his work over the next several weeks, during which he made additional images and showed that the rays darkened a photographic plate. Finally, he submitted his manuscript, *Über eine neue Art von Strahlen* ("On a New Kind of Rays") to the Physikalisch-Medizinische Gesellschaft in Würzburg on December 28, 1895.[7] In this paper he used the term "x-rays" for the first time. The first published account of his work appeared in *The Presse* of Vienna on January 5, 1896. *The Presse* noted, regarding the demonstration of bones,

> The surgeon could then determine the extent of a complicated bone fracture without the manual examination which is so painful to the patient: he could find the position of a foreign body such as a bullet or a piece of shell much more easily than has been possible heretofore and without any painful examinations with a probe.[2(p455)]

Once Röntgen presented his work in Würzburg, word of his achievement spread rapidly. This rapid spread was accompanied by an almost immediate appreciation of some of the possible uses of his rays, as well as almost immediate application in a variety of situations.

The day after Röntgen's announcement, Dr J. R. Ratcliffe in Birmingham, England, produced a radiograph of his hand after he had pushed a sterilized needle under the skin of his palm. The film, of course, demonstrated the location of the needle. The following night, a woman came to Queen's Hospital in Birmingham with a needle embedded in her hand. Ratcliffe and colleague Hall-Edwards made a radiographic image of her hand and developed a bromide print of the radiograph. They gave the print to the patient, who took it to her surgeon the next morning. The surgeon used the photograph as a guide in removing the needle. This was presumably the first operation to be done based on the results of diagnostic x-ray images.[2]

Radiographic images were being produced in several sites in Germany in January 1896, the same month that Röntgen's discovery was announced. Electronic communications resulted in a rapid transmission of the news to the United States as well. American newspapers published the news of Röntgen's discovery as early as January 9, 1896.[7] By the third week of January, a New York newspaper reported that x-ray images had been used in Europe to locate foreign objects and diagnose diseases of bone.[8] Although it has been reported that x-ray photographs were being produced in this country in January 1896,[9] the first documented diagnostic x-ray photograph in the United States may be one obtained in the physics department of Dartmouth College, Hanover, New Hampshire, on February 3, 1896. This film of the left wrist of a 14-year-old boy who fell while ice skating showed an ulnar fracture.[9]

Radiology developed rapidly as a medical and scientific discipline. In 1896 x-ray images were used to demonstrate a wide variety of skeletal abnormalities and foreign bodies. The British are credited with the initial use of radiographs in treating those wounded in battle that same year. Images of various organs, the fetus in utero, and the calcification of tissues were also produced.[2]

Röntgen had noted the difficulties in using x-ray images for the diagnosis of abnormalities involving tissues other than bone. To overcome this limitation, in February 1896 blood vessels were injected after death with a mixture of lime, cinnabar, and petroleum to demonstrate vascular anatomy.[3] The following year in Boston, Massachusetts, swallowed bismuth subnitrate was used to study the gastrointestinal tract of animals, and this technique was used in humans in 1898.[10]

Technical developments in 1896 included the use of fluoroscopy and cineradiography. Applications included submitting x-ray images as evidence in medicolegal cases, quality control in manufacturing metal products, detecting fraudulent documents and paintings, and inspecting postal parcels, all introduced in that same year.[2]

The widespread clinical use of x-rays was facilitated by scientific investigation and industrial application shortly after Röntgen reported his findings. Thomas Edison, who had invented the electric light bulb in the 1880s, began research on x-rays at his Edison Lamp Works in 1896. Among his studies were investigations of the source of x-rays, the tube to focus the rays, and the chemical substances that fluoresced when struck by x-rays. These last studies were important in the development of the Edison fluorescent lamp.[11]

A major advance occurred in 1913 at General Electric. The Crookes tube that Röntgen had used had been filled with gas, resulting in an erratic output of x-rays. Coolidge at General Electric used a cathode vacuum tube that produced a stable emission of x-rays. Later he introduced a tungsten alloy for both the cathode and the anode, and tungsten has been used for this ever since.[12] Interestingly, Edison had used calcium tungstate in his experiments, coating the inner walls of a vacuum tube into which x-rays were introduced. He envisioned a new type of lamp, but abandoned his research because of the adverse effects that resulted (described later).[11]

In addition to the development of better sources of x-rays, several other advances in the first few decades of radiology were crucial in facilitating the broad application of this diagnostic technique. Up to the 1920s, the x-ray-sensitive material was coated onto a glass plate. In the 1920s, the glass plate was replaced by celluloid film. Each piece of film contained a single x-ray image, and the film had to be changed after each picture was taken. The celluloid film was replaced with acetate, but this was a minor improvement in comparison to the next change. In 1931 the process was changed so that the x-ray-sensitive emulsion was applied to paper rather than film (R. J. Anderson, "In Search of TB Cases," *American Lung Association Bulletin*, March 1982, pp 11-13). In addition, multiple images could be applied to a single piece of paper as improvements in cameras and x-ray machines allowed for smaller images in some situations. These developments greatly reduced the time consumed in taking an x-ray image and reduced the cost from between $5 and $15 per picture to between 50 cents and a dollar. While these other technical advances were under way, there was also interest in reducing the time of exposure necessary for producing clinical radiographic images. This interest was driven partly by the practical need to be more efficient in processing patients. Early films required 15 minutes of exposure to x-rays to demonstrate the coarse structure of the bones of the hand. Thicker bones required longer exposures, so that a skull film might require an hour or more of exposure with the tube only 5 cm (2 in) from the head.[2] As discussed later, the recognition of toxic effects of exposure to x-rays also mandated attempts to reduce radiation exposure.

The development of intensifying screens was critical in reducing the amount of radiation necessary for the production of clinical radiographs. These screens (as currently used) are placed on each side of the x-ray film, forming a sandwich. The intensifying screen contains a fluorescent substance that produces fluorescent light when struck by x-rays, thus converting radiant energy to light energy. The x-ray film itself is extremely sensitive to light energy and reacts to the light produced by the intensifying screens, resulting in the final image. The use of intensifying screens reduces the amount of radiation necessary for the production of a clinical radiograph by a factor of $\frac{1}{15}$ to $\frac{1}{30}$ of that which would be necessary if there were no intensification.[12] This proved to be important in minimizing toxicity, in reducing the time necessary to make a diagnostic image, and in improving quality by reducing the motion of patients.

Tuberculosis was a leading cause of death in the United States in the latter part of the 19th century and remained one of the leading causes of death during the first few decades of this century, with a national death rate of 113 per 100,000 per year in 1920.[13] The rapid development of diagnostic radiology was widely applied to tuberculosis and proved to be critically important in the early detection of disease and the early institution of isolation. In the early years, there was debate about the relative merits of fluoroscopy and radiography in the diagnosis of tuberculosis, the former being less expensive, more rapid, and easier to interpret.[14] The technical developments outlined earlier led to the adoption of radiography rather than fluoroscopy as the major imaging technique for tuberculosis. Fluoroscopy, however, claimed an important role with the introduction of collapse therapy, that is, the creation of a therapeutic pneumothorax.[14]

The increased efficiency of making images and the decreased cost allowed the application of x-ray images to tuberculosis screening programs, and mass x-ray screening became the primary tool for tuberculosis control programs and remained so until the incidence of tuberculosis decreased sufficiently for the tuberculin skin test to be useful. The extent to which x-ray images were implemented is shown by the fact that in 1946, 6 million screening x-ray films were taken by public health screening programs in the United States. By 1950 the number had increased to 15 million.[15] With the development of antimicrobial therapy for tuberculosis treatment and subsequently for treating tuberculosis infection and preventing disease, radiography took on yet another crucial role in tuberculosis control.

Although the decrease in the tuberculosis incidence led to the elimination of mass screening for tuberculosis, diagnostic radiology continued to grow at a rapid pace after 1950, a pace that has not slowed yet. An estimated 260 to 330 million radiologic procedures were done in the United States in 1990. This is an average of 1.0 to 1.3 radiologic procedures per citizen per year. The estimated cost was $19 to $22 billion, representing about 3.5% of the total national spending on health care.[16] At the Massachusetts General Hospital Medical Center alone, in 1992 there was a staff of 69 full-time practicing radiologists with a case load of more than 400,000 cases per year.[17] New developments continue, as does the rapid growth in the application of these new developments. Magnetic resonance (MR) imaging was first used clinically in 1982. Before October 1984, there were 72 MR units operational in the United States, and in 1990, 70 of these units were still operational. (There were, of course, many new MR units by that time.) In 1990, each of these 70 units performed an average of more than 3,000 examinations per year, for a total of 210,000 procedures from these 70 oldest units alone.[18]

The toxicity of x-rays became apparent soon after Röntgen discovered them. Hair loss was noted first, being recognized by May 1896. Skin toxicity was noted a few months later. Early x-ray images required exposures of as long as 80 minutes, and thus early x-ray workers were among the most severely affected. Dr Hall-Edwards, the British physician responsible for the first clinical x-ray photograph in England in early 1896, developed cancer of the hands from radiation exposure incurred while holding patients' extremities on photographic plates. In 1896, a commercial demonstrator at Bloomingdale Brothers store in New York, whose x-ray machine ran continuously for two to three hours a day, reported the development of dry skin, followed by changes similar to a strong sunburn and later scaliness of the skin. He also noted the cessation of fingernail growth and loss of hair from involved portions of the skin.[3] That same year Sir Joseph Lister postulated that

> the transmission of the rays through the human body may be not altogether a matter of indifference to internal organs, but may by long continued action produce, according to the condition of the part concerned, injurious irritation or salutary stimulation.[3(p91)]

Because of the erratic output of x-rays from the old gas-evacuated tubes, early radiologists had to examine their own hands with a fluoroscope to measure the output and gauge the needed exposure time for clinical radiographs.[17] Cancer of the skin of the hands was a major occupational health hazard for these early pioneers.[2]

Toxicity played a major role in Edison's decision to abandon his development of a new lamp using x-rays.[19] His assistant Clarence Dally suffered hair loss and skin ulcers. He had periodic acute inflammation of his left hand, with which he held the objects in the x-ray beam. Carcinoma of both of his hands developed, leading to bilateral amputation of the arms, and he died in 1904 of recurrent carcinoma.[11] Walter James Dodd, the first skiagrapher (equivalent to today's radiologist) at the Massachusetts General Hospital, died in 1916 of radiation exposure and a series of surgical procedures resulting from that exposure.[17]

Ironically, Röntgen had conducted virtually all of his experiments in a zinc box, which gave better definition of the x-ray beam. He had also added a lead plate to the zinc and thus fortuitously protected himself from the radiation that he discovered.[3]

The therapeutic use of x-rays was initiated shortly after Röntgen's discovery. The first reported case, a patient with carcinoma of the breast, was treated in 1896.[20] An increased therapeutic use of x-rays followed the observation of the destructive effects of x-rays on normal tissues. Unstandardized x-ray treatments were used in the first part of the 20th century. The first treatments using quantitated and qualitated doses of radiation were based on studies from the Frauenklinik (Women's Clinic) at Freiburg University in Germany. These studies were published in 1918.[3]

The French scientist Henri Poincaré postulated that because x-rays cause fluorescence, fluorescent substances might generate x-rays. His countryman, Henri Becquerel, confirmed that uranium produced similar rays, that is, gamma rays. Two other scientists working in France, Marie and Pierre Curie, identified other radioactive substances, among them radium,[21] which they discovered in 1896, and published their report in 1898.[22]

As noted earlier, the first standardization of x-ray therapy was at Freiburg. The pioneering studies of therapy using gamma rays from radium were carried out in the same institution.[3] Over the ensuing decades, there has been progressively greater usage of radiation therapy. In 1990, nearly 500,000 patients in this country were treated with radiation therapy.[23] Röntgen's discovery also provided the scientific basis for diagnostic nuclear medicine, another discipline that has experienced dramatic growth.

Röntgen was a modest man who shunned publicity. As with many who make dramatic discoveries, he was also the subject of much criticism. There were a number of reasons for this. One was the fact that others, for example, Goodspeed in Philadelphia, Pennsylvania, and Crookes in England, had made accidental x-ray photographs in the course of their studies. Neither had appreciated the importance of nor sought to explain their findings.[24]

Lenard himself had also noted the effects of x-rays, without appreciating the importance of his observation. At first he had been helpful to and supportive of Röntgen. It appears that his attitude may have changed after he sent Röntgen a letter of congratulations in 1897, expecting a reply acknowledging his own contributions. He never received such a letter. With the passage of time, he became increasingly bitter.[6] This hostility may have hardened when Röntgen received the first Nobel prize for physics in 1901. Lenard himself received the Nobel prize for physics in 1905, and his Nobel lecture was critical of Röntgen. Lenard subsequently became one of the leading scientists of Nazi Germany and a staunch supporter of the Nazis. There was then political reason to downplay the role of Röntgen and to advance the case for Lenard as the one who should receive credit for the discovery of x-rays.[6] Rumors had circulated shortly after Röntgen's discovery that the discovery had been accidental or that an assistant rather than Röntgen himself had made it.[24] Such rumors persisted after Röntgen's death and were advanced over the years by Lenard's supporters.

Röntgen was so embittered by the criticism and claims that he received credit for the work of others that he never published any material on x-rays after his initial three publications between 1895 and 1897.[8] Although he and others quickly recognized the importance of his discovery, no one could have anticipated the role of Röntgen's rays in medicine, science, and industry a century later. November 8, 1995, marked the 100th anniversary of a momentous discovery that bears recognition from all scientists.

REFERENCES

1. Gomez GE: Tribute to Wilhelm Conrad Röntgen. Am J Roentgenol Radiat Ther 1948; 60:96-103

2. Brailsford JF: Roentgen's discovery of x rays—Their application to medicine and surgery. Br J Radiol 1946; 19:453-461

3. Glasser O: Dr. W. C. Röntgen, 2nd edition. Springfield, Ill, Charles C. Thomas, 1958

4. Glasser O: Chronology of Röntgen's life. Am J Roentgenol Radiat Ther 1945; 54:541-552

5. Sante LR: Manual of Roentgenological Technique, 16th revised edition. Ann Arbor, Mich, Edwards Brothers, 1952

6. Etter LE: Some historical data relating to the discovery of the roentgen rays. Am J Roentgenol Radiat Ther 1946; 56:220-221

7. Hille H: From the memoirs of a student in Röntgen's laboratory in Würzburg half a century ago. Am J Roentgenol Radiat Ther 1946; 55:643-647

8. Spiegel PK: The first clinical x-ray made in America—100 years. AJR Am J Roentgenol 1995; 164:241-243

9. Glasser O: Early American roentgenograms. Am J Roentgenol Radiat Ther 1945; 54:590-594

10. Crandall DL, Barger A, Clifford HP: Bowditch's forgotten contributions to radiology. AJR Am J Roentgenol 1993; 161:1105-1108

11. Brown P: Clarence Madison Dally (1865-1904). AJR Am J Roentgenol 1995; 164:237-239

12. Thompson TT: Primer of Clinical Radiology. Boston, Mass, Little, Brown, 1980

13. Stead WW, Dutt AK: Epidemiology and host factors, chap 1, *In* Schlossberg D (Ed): Tuberculosis, 3rd edition. New York, NY, Springer-Verlag, 1993, pp 1-15

14. Keers RY: Pulmonary Tuberculosis—A Journey Down the Centuries. London, England, Baillière Tindall, 1978

15. Blakeslee AL: And the Spark Became a Flame. Queensboro, NY, Queensboro Tuberculosis and Health Association, National Tuberculosis Association, Brooklyn Tuberculosis and Health Association, Powers X-ray Products, Inc, 1954

16. Sunshine JH, Mabry MR, Bansal S: The volume and cost of radiologic services in the United States in 1990. AJR Am J Roentgenol 1991; 157:609-613

17. Wyman SM: Department of Radiology, Massachusetts General Hospital: A brief history. AJR Am J Roentgenol 1993; 160:1141-1144

18. Evens RG, Evens RG Jr: Analysis of economics and use of MR imaging units in the United States in 1990. AJR Am J Roentgenol 1991; 157:603-607

19. Cullinan J, Cullinan A: Early fluoroscopic imaging. Radiol Technol 1994; 66:119-124

20. Brady LW: Gold Medal Address: The Radiation Therapy Oncology Group—1987. Int J Radiat Oncol Biol Phys 1988; 15:537-542

21. Miller WT: Introduction to Clinical Radiology. New York, NY, Macmillan, 1982

22. Curie P, Curie Mme P, Bemont G: Sur une nouvelle substance fortement radioactive contenue dans la pechblende. Compt Rand Acad Sce (Paris) 1898; 127:1212-1217

23. Owen JB, Coia LR, Hanks GE: Recent patterns of growth in radiation therapy facilities in the United States: A patterns of care study report. Int J Radiat Oncol Biol Phys 1992; 24:983-986

24. Glasser O: Strange repercussions of Röntgen's discovery of the x-rays. Radiology 1945; 45:425-427